Major Scientific Discoveries

The Space Shuttle and Great Observatories

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Space Shuttle Bestows On Hubble the Gift of "Perpetual Youth"
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NASA's "Great Observatories" are symbolic of our urge to explore what lies at the edge of the universe, as we know it. Humans had stared at the stars for centuries before the advent of simple telescopes brought them a little closer to the amazing formations in our solar system. Telescopes became larger, technologies were developed to include invisible wavelengths from the shortest to longest, and locations of instruments were carefully chosen to gain better sights and insights into our vast universe. Then, the Space Age dawned and we sent humans to the moon. The desire to explore our universe became even more intense. NASA probes and rovers landed on destinations in our solar system—destinations we once thought remote and beyond reach. These initiatives forever changed our perception of the solar system and galaxies.

Scientists have long desired space-based observation platforms that would provide a better view of our universe. NASA's Great Observatories (satellites) are four large and powerful space-based telescopes that have made outstanding contributions to astronomy. The satellites are:

- *Hubble Space Telescope*
- *Compton Gamma Ray Observatory*
- *Chandra X-ray Observatory*
- *Spitzer Space Telescope*

Of these, only the Spitzer Space Telescope was not launched by the Space Shuttle. In June 2000, the Compton Gamma Ray Observatory was deorbited and parts splashed into the Pacific Ocean.

While Hubble has become the people's telescope due its public and media impact, all the Great Observatories made enormous science contributions including: new wave bands; high-resolution, high-sensitivity observations; and a sharper, deeper look into distant galaxies.

Space Shuttle Bestows On Hubble the Gift of "Perpetual Youth"

The Space Shuttle and Hubble Space Telescope were conceived and advocated as new NASA programs in the same era—roughly the late 1960s and the decade of the 1970s. It was recognized early on that a partnership between the Hubble program and the Space Shuttle Program would be mutually beneficial at a time when both were being advocated to Congress and the Executive Branch.

A telescope designed to be periodically serviced by astronauts could be viewed as a "permanent" astronomical observatory in space, modeled after the observatories on Earth's surface. At Hubble's core would be a large, high-quality optical telescope that, with its surrounding spacecraft infrastructure periodically serviced by shuttle crews, could have an operating lifetime measured in decades. Its heart would be scientific instruments that could be regularly replaced to take advantage of major advances in technology. Thus, the shuttle brought to Hubble the prospect of a long life and, at the same time, the promise of "perpetual youth" in terms of its technological prowess.

Hubble Space Telescope after capture by STS-61 (1993).

Hubble provided a splendid example of the value of the shuttle in allowing regular access to low-Earth orbit for a large crew and heavy payloads. The shuttle enabled modes of working in space that were not otherwise possible, and the Hubble program was both the proof of concept and the immediate beneficiary. The two programs represented the nexus of human spaceflight and robotic exploration of the universe.

Hubble's design was optimized with its relationship to the shuttle in mind. The optical telescope and surrounding structure needed to be small enough to fit into a shuttle payload bay. On the other hand, the scientific value of the telescope hinged on making its aperture as large as possible. The final aperture size, 2.4 m (7.9 ft), was large enough to allow one of the observatory's most important science objectives—precisely measuring the distance scale and age of the universe—yet could be packaged to fit inside the shuttle payload bay.

Many of the Hubble spacecraft's subsystems were designed in modular form, and were removable and replaceable with relative ease by astronauts in spacesuits. However, this was not the case for every subsystem. One of the most telling demonstrations of the value of human beings working in space comes from the creativity and ingenuity of the astronauts and their engineering colleagues on the ground in devising methods for replacing or repairing components that were not designed to be worked on easily in orbit.

It is well known that Hubble, launched in 1990, was seriously defective. Its 2.4-m (7.9-ft) primary mirror—a beautifully ground and polished optic—was accidentally ground to the wrong prescription. The result, which became apparent when the newly launched telescope first turned its gaze to starlight, was a blurry image that could not be corrected with any adjustments in the telescope's focus mechanism or with the 24 actuated pressure pads placed under the primary mirror to adjust its shape, as needed. The erroneous curvature of the mirror produced a common form of optical distortion called "spherical aberration." In addition, Hubble's two flexible solar arrays shuddered significantly due to thermal stresses introduced every time the spacecraft passed from darkness to daylight or vice versa. This phenomenon introduced jitter into the pointing of the telescope, further smearing out its images.

In the years immediately after Hubble's deployment, the observatory did produce some interesting astronomical science but nothing at all like what had been expected throughout its design and development. It quickly became a national embarrassment and the butt of jokes on late-night talk shows.

It is interesting to consider how the history of Hubble and NASA might have transpired if the spacecraft had not been designed as an integral part of the world of human spaceflight but, rather, had been launched with an expendable rocket and not been serviceable in space. The scandal and embarrassment would likely have persisted for a while longer and then faded as the less-than-memorable science being produced also faded from public interest. One wonders if the champions of the Hubble mission could have stimulated the political and public will to try again—to develop and launch a second Hubble. Certainly, any such project would have taken a decade or longer and required new expenditures of public funds, probably $2 billion or more. In any event, the original Hubble Space Telescope would have long ago failed and today would be orbiting Earth as a large and expensive piece of space junk.

Hubble's history has played out in an entirely different and much more satisfying manner precisely because it was built to be cared for by human beings in low-Earth orbit. Scientists and engineers quickly identified the nature of Hubble's optical flaw and created optical countermeasures to correct the telescope's eyesight. The European Space Agency devised a new thermal design to mitigate the jitter-inducing flexure of the European solar arrays. The time required to design, fabricate, test, and fly these fixes to Hubble on the first servicing mission was approximately 3.5 years. In late 1993, public scorn turned into adulation, both because of the exquisite imagery that a properly performing Hubble returned to the ground and the heroism of the astronauts and the dedication of a team of NASA employees and contractors who refused to give up on the original dream of what Hubble could accomplish. The public image of NASA as a "can-do" agency certainly received a major boost. The techniques of working with precision on large structures in space surely contributed to the acceptance of the feasibility of constructing the International Space Station.

The possibility of periodically servicing Hubble added a degree of flexibility, timeliness, and creativity that was not possible in the world of robotic science missions, which must be planned and executed over periods of many years or even decades. Hubble's scientific capabilities have never grown out of date because it was regularly updated by shuttle servicing. It is the most in-demand, scientifically successful, and important astronomical observatory in human history, after Galileo's original telescope. Arguably, it is one of the most important scientific instruments of any kind. There is simply no way this level of achievement could have been possible without the Space Shuttle.

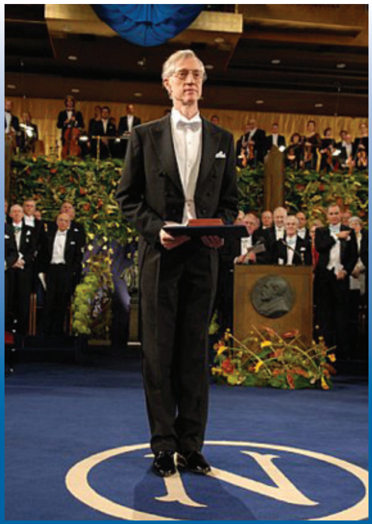
Hubble—A Work of Ingenuity

On September 9, 2009, NASA declared Hubble to be in full working order following the tremendously successful fifth shuttle mission to service the telescope. As a result of coordination across the extensive Hubble team, the crew of Space Shuttle Atlantis (Space Transportation System [STS]-125) left behind an essentially new telescope with six working instruments. Two superb instruments—the Wide Field Camera 3 and the Cosmic Origins Spectrograph—replaced older devices. Two instruments that had suffered electronic failure in flight were restored to working order through repair activities that, to date, were the most ambitious ever attempted in space. Specifically, the Advanced Camera for Surveys and the Space Telescope Imaging Spectrograph were returned to service to make Hubble the most powerful optical telescope in the world. The STS-125 spacewalks were long and arduous, presenting unforeseen challenges over and above the demanding activities scheduled on the manifest; however, the payoff, seen in the first data, was the reward.

At the launch of STS-125, hopeful astronomers were already planning more research programs using the advanced capabilities of the new telescope. They were confident in the knowledge that over Hubble's 19-year track record, the telescope had greatly surpassed expectations and would continue to do so. Hubble is not the facility that eminent scientist Lyman Spitzer envisioned in the 1940s; it has dramatically exceeded the imagination of all who contributed to the dream of such a capable observatory.

John Mather, PhD

Nobel Prize in Physics (2006). Senior project scientist for the James Webb Space Telescope, Goddard Space Flight Center.



"The Space Shuttle is a 'brilliant engineering' accomplishment but it was a poor decision on the part of senior leadership as it 'swallowed' other expendable launch vehicles. This decision was not well received by members of the science community.

"The Hubble Space Telescope was conceived and designed to be repaired by the shuttle. In that shuttle had brilliant success. What would have been a 'black eye' forever for American science, the shuttle made the capabilities of Hubble 10 times better, over and over with each servicing mission. In addition to the significant repairs, the shuttle greatly expanded the capabilities of the Hubble by upgrading several key components. The upgrades have allowed superlative science to be accomplished from the Hubble. What has been learned from the Hubble is being used in assembling the James Webb Space Telescope. In my view, there would be no Hubble telescope without the Space Shuttle and no James Webb Space Telescope without the Hubble.

"In many ways, the most important scientific contribution of the Space Shuttle was that it kept the agency (NASA) alive after the Apollo Program. Thus it kept science alive at NASA indirectly.

"Human spaceflight captures people's imagination at gut level. The Space Shuttle was also a product of the Cold War environment of the nation. Humans go into space for more than just science."

The fidelity of Hubble's wide-field imagery is superb because the telescope's exquisite optical quality is not limited by the jitter and distortion caused by the shifting atmosphere that affect images obtained from the ground. Additionally, as instruments with new technologies—primarily more sensitive light detectors—were placed on board, additional wavelengths of light blocked by the Earth's atmosphere could be detected in the ultraviolet region of the spectrum where the Earth's atmosphere is opaque, and for some regions of the infrared that suffer from absorption due to water vapor and other molecules.

Hubble has been a crown jewel in the Space Shuttle Program, providing scientific return and unparalleled public acknowledgment over its lifetime. Launched by STS-31 in 1990, Hubble has contributed to every aspect of astrophysics, achieved its original design goals, and opened new areas of investigation not envisioned in the original proposals for its construction.

Shuttle-enabled refurbishments of Hubble have allowed astronomers to:

- Determine the expansion rate of the universe to 5% accuracy (10% was the goal)
- Discover the existence of dark energy (unexpected) and thus resolve the age of the universe to be 13.7 billion years old
- Identify the host objects for powerful gamma-ray bursts
- Observe some of the deepest images of the cosmos
- Discover protoplanetary disks
- Observe chemical constituents of the atmospheres of planets orbiting other stars
- Characterize the nature of black holes, from supermassive objects in galaxies to stellar-sized objects in star clusters
- Explore numerous views of solar system objects revealing planetary weather and distant dwarf planets still bound to the sun

There were early times in the Hubble program, however, when such amazing accomplishments seemed unachievable.

Astronomical Terms

Astronomical unit: A unit of length used for measuring astronomical distances within the solar system equal to the mean distance from Earth to the sun, approximately 150 million km (93 million miles).

Black hole: Formed when the core of a very massive star collapses from its own gravity. A black hole has such a strong pull of gravity that not even light can escape from it.

Dark energy: Dark energy is inferred from observations of gravitational interactions between astronomical objects and is not directly observed. It permeates space and exerts a negative pressure.

Dark matter: Physicists infer the existence of dark matter from gravitational effects on visible matter, such as stars and galaxies. It is a form of matter particle that does not reflect or emit electromagnetic radiation.

Galaxy: A collection of stars, gas, and dust bound together by gravity. The largest galaxies have thousands of billions of stars.

Light-year: The distance that light travels in a vacuum in 1 year, approximately 9.46 trillion km (5.88 trillion miles).

Nebula: A diffuse mass of interstellar dust or gas or both, visible as luminous patches or areas of darkness depending on the way the mass absorbs or reflects incident radiation.

Planetary nebulae: A nebula, such as the Ring Nebula, consisting of a hot, blue-white central star surrounded by an envelope of expanding gas.

Quasars: Celestial objects that emit extremely high levels of electromagnetic radiation (including light). The amount of energy emitted by a quasar is higher than even the brightest stars. The closest known quasar is 780 million light-years away.

Supermassive black hole: A gigantic black hole, with a mass ranging from millions up to billions of times the mass of our sun, residing at the core of almost every galaxy.

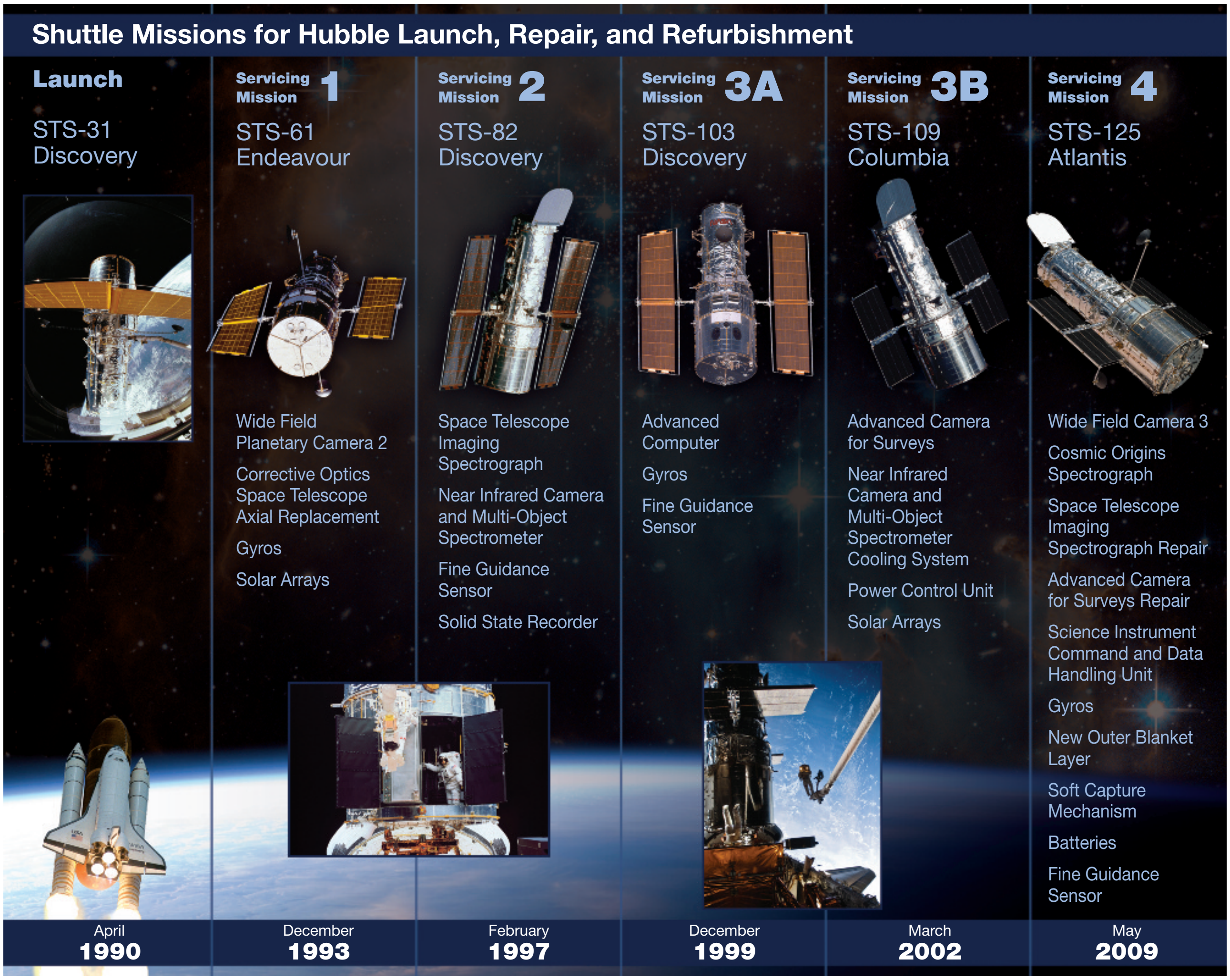
Supernova: The explosive death of a massive star whose energy output causes its expanding gases to glow brightly for weeks or months. A supernova remnant is the glowing, expanding gaseous remains of a supernova explosion.

The Launch of Hubble—First Results

On April 24, 1990, Hubble was launched into orbit with Space Shuttle Discovery (STS-31). The shuttle carried five instruments: the Wide Field Planetary Camera; the Goddard High Resolution Spectrograph; the Faint Object Camera; the Faint Object Spectrograph; and the High Speed Photometer.

During the years of advocacy for the telescope and the subsequent detailed design period, astronomers described some of the amazing results that would be forthcoming from Hubble; however, the much-anticipated first images showed, quite clearly, that something was amiss with the telescope.

Despite their disenchantment, astronomers worked hard to understand and model the Hubble images, and interesting research was accomplished nonetheless. In the first year, the campaign to characterize the nature of black holes in the universe was initiated with the confirmation that a



supermassive black hole with mass about 2.6 billion times the mass of the sun resides in the center of the giant elliptical galaxy M87. This result was based on Wide Field Planetary Camera and Faint Object Camera imagery and Faint Object Spectrograph spectroscopy. In addition to that scientific result, optical counterparts of radio jets in galaxies were resolved, spectroscopic observations helped to disentangle the nature of intergalactic clouds absorbing light from near and far galactic systems, and the monitoring of surface features of solar system planets was initiated.

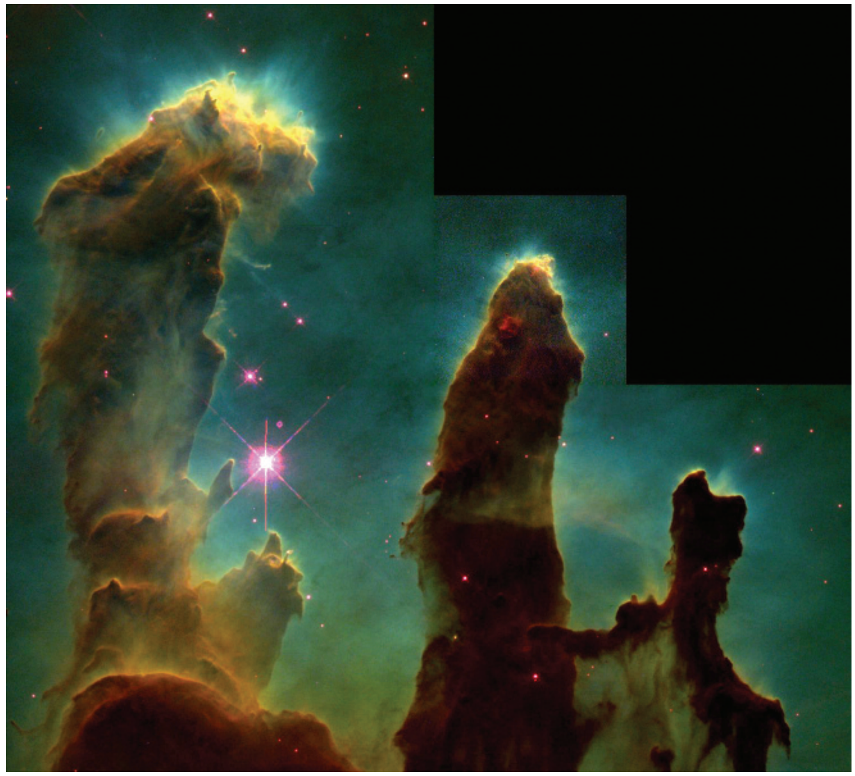
Servicing Mission 1

To correct for the telescope's optical flaw, Hubble scientists and engineers designed and fabricated a new instrument, the Wide Field Planetary Camera 2, and another device called Corrective Optics for Space Telescope Axial Replacement, the latter intended to correct the instruments already on board. The first Hubble servicing mission (STS-61 [1993]) was the ambitious shuttle flight to install the corrective optics and resolve other spacecraft problems. It was a critical mission for NASA. The future of the Hubble program depended on the astronauts' success, and the Space Shuttle Program hung in the balance as well as the future of the agency. The struggle to keep the first repair mission funded was a day-by-day battle that served to cement the cooperation between NASA and the university research community.

As the first images came into focus, overjoyed researchers and engineers began to gain confidence that the promise of Hubble could now be realized.

New Results After Servicing Mission 1

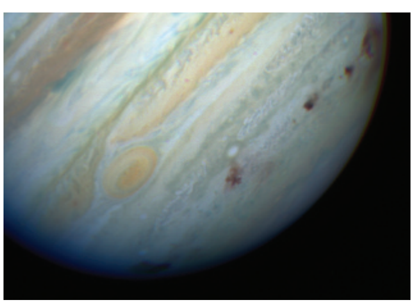
Immediately, NASA obtained impressive results. For example, Wide Field Planetary Camera 2 images of the Orion Nebula region resolved tiny areas of compact dust around newly formed stars. These protoplanetary disks, sometimes called *proplyds*, were the first hint that Hubble would contribute in a significant way to the studies of the formation of extrasolar planetary systems. In another observation, Hubble detected a faint galaxy around a luminous quasar (short for quasi-stellar object), suggesting that luminous quasars and galaxies were fundamentally linked. In our own galaxy, the core of an extremely dense, ancient cluster of stars—the globular cluster 47 Tucanae—was resolved, demonstrating definitively to the skeptical scientific community that individual stars in crowded fields could be distinguished with the superb imaging power of Hubble.



Gas pillars in the Eagle Nebula: Pillars of Creation in star-forming region captured by the Wide Field Planetary Camera 2 in 1995. The region is trillions and trillions of miles away in the constellation Serpens. The tallest pillar is 4 light-years long and the colors show emissions from different atoms.

Shoemaker-Levy

Early Hubble observations of solar system objects included the spectacular crash of Comet Shoemaker-Levy 9 into Jupiter in 1994. This event was witnessed from start to finish, from the first fragment impact to the aftermath on the Jovian atmosphere. Images were also taken in visible blue light and ultraviolet light to determine the depth of the impacts and the nature of Jupiter's atmospheric composition.



Color image of Jupiter showing the effect of the several impacts of Comet Shoemaker-Levy 9 after its multiple fragments impacted the planet in 1994.

Pillars of Creation

The famous "Pillars of Creation" image of the Eagle Nebula captured the public imagination and contributed to the understanding of star-formation processes. The images captured in 1995 with Wide Field Planetary Camera 2 showed narrow features protruding from columns of cold gas and dust. Inside the gaseous "towers," interstellar material collapsed to form young stars. These new hot stars then heated and ionized the gas and blew it away from the formation sites. The dramatic scene, published in newspapers far and wide, began to redeem the public reputation of Hubble.

Existence of Supermassive Black Holes

From ground-based data, scientists knew that galaxies exhibit jets and powerful radio emission that extends well beyond their optical periphery. Huge x-ray emissions and spectroscopic observations of galaxies suggested that some of these objects might contain a large amount of mass near their centers. Even Wide Field Planetary Camera 2 observations of the innards of several galaxies suggested that black holes might be hidden there. However, it was the observation of the giant elliptical galaxy M87 with the Faint Object Spectrograph that conclusively demonstrated that supermassive black holes exist in large galaxies. This was the turning point in black hole studies, with spectroscopy being the powerful diagnostic tool astronomers could use to begin the Hubble census of these exotic objects.

Building Blocks of Early Galaxies

One of the planned goals for Hubble research was to understand the nature of the universe and look back in time to the earliest forming galaxies. In December 1995, 2 years after the first servicing mission, Hubble's Wide Field Planetary Camera 2 was pointed at a field in Ursa Major for 10 days, accumulating 342 exposures. The final image—the Hubble Deep Field—was, at the time, the deepest astronomical image ever acquired. The field probes deep into the universe and contains over 1,500 galaxies at various distances.

After the Hubble Deep Field data were produced, telescopes were pointed at the same part of the sky to obtain data in every conceivable way. Besides bolstering the idea that galaxies form from building blocks of smaller components that are irregularly shaped and that the rate of star and galaxy formation was much higher in the past, analysis of the data pushed the observable universe back to approximately 12 billion years. Papers written on Hubble Deep Field data alone number in the hundreds and document a new understanding of cosmological and astrophysical phenomena.

The immediate release of Hubble Deep Field data represented a watershed in astronomical research as well. A new method was born for concentrating astronomical facilities and the collective brainpower of the scientific community on a specific research problem. Thus, the Hubble Deep Field represents not only a leap forward in scientific understanding of the universe, but a significant alteration in the way astronomy was conducted.

Edward Weiler, PhD
Chief scientist for the Hubble Space Telescope (1979-1998).
NASA associate administrator, Science Mission Directorate.

"It's fair to say that Hubble, today, would be a piece of orbiting space debris if it hadn't been for the Space Shuttle Program. If Hubble had been launched on an expendable launch vehicle, we would have discovered the optical problem yet been unable to fix it. Hubble would have been known as one of the great American scientific disasters of our time. Hubble's redemption is due to the Space Shuttle Program and, most importantly, to the astronauts who flew the shuttle and did things (in repairing Hubble) that we never thought could be done in space. Hubble became a symbol of excellence in technology and science, and the shuttle made that happen.

"I've spent 34 years on Hubble in one way or another. I was on top of Mount Everest at the launch, with all of us astronomers who had never done an interview. I was on the Today Show *and* Nightline *on the same day. I experienced the ecstasy in April 1990, to the bottom of the Dead Sea 2 months later when a spherical aberration was detected in the Hubble. In our hearts, we knew we could fix it. We promised the press we would fix it by December 1993, and nobody believed us. Then, on December 20, 1993, we saw the first image come back. It was spectacular. It was fixed. And the rest is history. We went from the bottom of the Dead Sea back to the top of Mount Everest and beyond…we were elated!"*

Subsequent Servicing Missions

Servicing Mission 2

By the end of 1996, Hubble was a productive scientific tool with instruments for optical and ultraviolet astronomy. During the second servicing mission in February 1997, the STS-82 crew installed two new scientific instruments: the Near Infrared Camera and Multi-Object Spectrometer, extending Hubble's capabilities to the infrared, and the Space Telescope Imaging Spectrograph, offering ultraviolet spectroscopic capability. Astronomers now expanded their research to probe astrophysical phenomena using the excellent imaging performance of Hubble coupled with new capability over a larger range of wavelengths.

Servicing Missions 3A and 3B

The third servicing mission was intended to replace aging critical telescope and control parts to retain Hubble's superb pointing ability and to install new computer equipment and a new instrument; however, when a third (out of six) gyroscope on Hubble failed—three gyros are needed for target acquisition—NASA elected to split these missions into two parts. To add to the drama, a fourth gyroscope failed on November 13, 1999. Hubble was safe, but it could not produce scientific observations. Another bit of tension was created by concern about the transition to the year 2000 and the hidden computer problems that might occur. Just in time, on December 19, 1999, Space Shuttle Discovery (STS-103) delivered new gyroscopes, one fine guidance sensor, a central computer, and other equipment, restoring Hubble to reliable operation and making it better than ever.

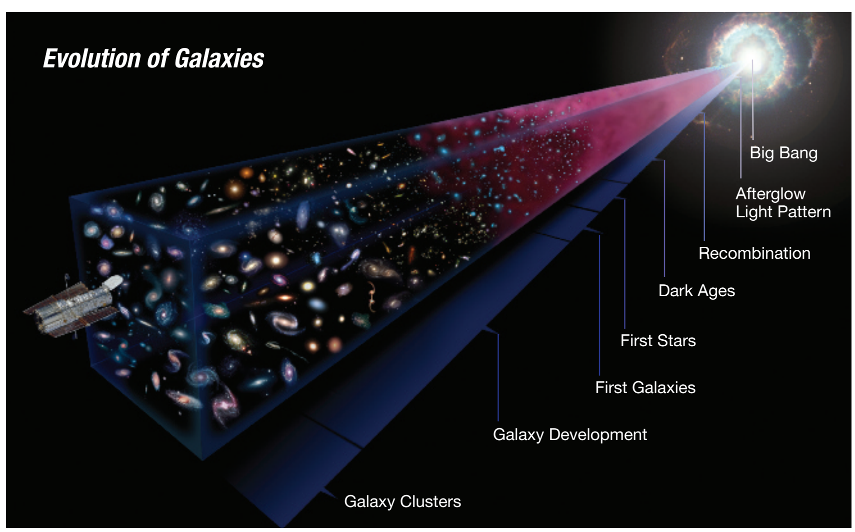
The next servicing mission occurred during March 2002 when Space Shuttle Columbia (STS-109) was launched to further upgrade the telescope. The new science instrument, the Advanced Camera for Surveys, was installed with a wide field of view, sharp image quality, and enhanced sensitivity. The Advanced Camera for Surveys field was twice that of the Wide Field Planetary Camera 2 and collected data 10 times faster. The astronauts also installed new solar array panels, a power control unit, and a new cooler for the Near Infrared Camera and Multi-Object Spectrometer to extend its life. They also installed a refurbished Fine Guidance Sensor and a reaction wheel to ensure telescope steering and fine pointing.

Hubble Deep Field and Hubble Ultra Deep Field

With the new infrared capability installed during the second servicing mission, astronomers turned the Near Infrared Camera and Multi-Object Spectrometer to view part of the original Hubble Deep Field for a series of long exposures. Extremely distant objects were revealed, objects that had been undetected in the optical Hubble Deep Field because their light was red-shifted due to the expansion of the universe. The original Hubble Deep Field is located in the northern celestial hemisphere. In 1998, NASA added a second field, the Hubble Deep Field-South, to the collection. The second field represented another "core sample" of the universe compared and contrasted to the northern observation to verify that Hubble Deep Field-North is representative of the universe in general. Researchers took advantage of Space Telescope Imaging Spectrograph and Near Infrared Camera and Multi-Object Spectrometer cameras to obtain deep adjacent fields as additional samples of the universe in the ultraviolet and infrared.

The Hubble Ultra Deep Field showing thousands of galaxies reaching back to the epoch when the first galaxies formed.

After astronauts installed Advanced Camera for Surveys during the third servicing mission, astronomers pushed the limits of observation even further in an additional field called the Hubble Ultra Deep Field. Deep Advanced Camera for Surveys and Near Infrared Camera and Multi-Object Spectrometer data revealed thousands of galaxies, some of which existed a mere 800 million years after the Big Bang. The optical detections reached 31 to 32 magnitudes, at least seven times deeper than ever before, and there were hints from the new Near Infrared Camera and Multi-Object Spectrometer data that galaxies as young as a few million years after the creation of the universe were detected. Observations with NASA's Spitzer Space Telescope produced deep images of the Hubble Ultra Deep Field in the infrared. These data were analyzed



Schematic of Hubble sampling galaxies through space and time.

along with the Hubble data to provide a more complete catalog of very distant galaxies with the result that at least one surprisingly massive galaxy was identified in the field where only small "precursor" galaxies were expected.

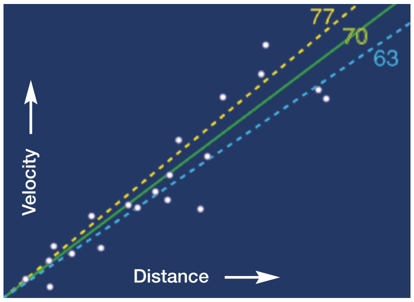
Astronomers were quick to test that result using Wide Field Camera 3, deployed during a servicing mission. The faintest galaxies found are blue and should be deficient in heavy elements, meaning they are from a population that formed extremely early when the universe was only 600 million years old. More data from Wide Field Camera 3 may reach even 100 million years earlier. Beyond that, astronomers anticipate continuing to push earlier in the universe with the launching of the James Webb Telescope.

Age of the Universe

The cornerstone investigation to be carried out by Hubble was the determination of the age of the universe. Previous work provided a wide range for this age: from 10 to 20 billion years old—a factor of two. Hubble research was to address one of the most basic questions about the cosmos, and further refinement was to be based on more accurate measurement of the cosmological expansion rate; i.e., the Hubble constant. From this expansion rate, the age of the universe can be determined by tracing the expansion back to the origin of cosmos. In fact, this key project was used as prime justification for fabrication of the telescope.

In particular, it was well known that data for variable stars called Cepheids were critical to answer this fundamental question. Cepheid variables were discovered in the early 1900s when Henrietta Leavitt studied photographic plate material while working at the Harvard College Observatory. She

The spiral galaxy NGC 4603 is the most distant galaxy used to study the pulsating Cepheid variables for the Hubble constant study. This galaxy is associated with the Centaurus cluster, one of the most massive groupings of galaxies in the closer universe. This image was assembled from Hubble Wide Field Planetary Camera 2 data obtained in 1996 and 1997.



This Hubble Diagram for Cepheids shows a plot of galaxy distance (determined from the Cepheid variables in it) vs. the velocity that the galaxy appears to be receding from Earth (determined from spectroscopy). The graph shows that the value of Hubble constant is the best fit from the key project observations.

carefully compiled a list of stars that changed brightness regularly in the nearby Large and Small Magellanic Clouds, companion galaxies to our own Milky Way. While classifying the subset of variable stars that were Cepheids, she noticed that objects with longer periods of variation were brighter. Her "period-luminosity" relation is the basis for the use of Cepheids as a standard to be used for distance measurements. Before Hubble observations were taken, distances to nearby galaxies had been determined from Cepheids using ground-based telescopes to map the local structure, motions, and expansion.

Since the results from many previous studies of the nearby universe produced such disparity, a goal of the Hubble observational program was to push the measurements out farther to more distant, fainter objects and determine Hubble constant with greater accuracy. It also was understood at the time of the launch of Hubble that the oldest objects known, the globular clusters, had ages of about 15 billion years, and this result served as an independent measure of the age of the universe (the universe has to be at least as old the objects in it).

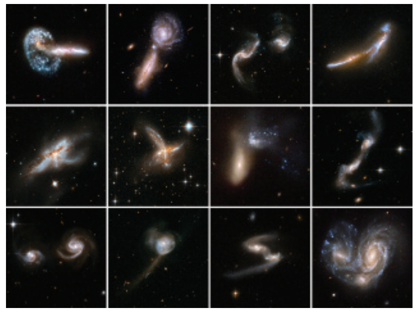
The key project team measured superb resolution Hubble Wide Field Planetary Camera 2 images over many years. The team identified nearly 800 Cepheids in 18 galaxies out to 65 million light-years. Data from 13 other galaxies were combined for a total of 31 galaxies with measured distances. The recession velocity of each galaxy was plotted against each galaxy's distance as measured from the Cepheids for a self-consistent measurement. This plot indicated the expansion rate exhibited by the benchmark galaxies was within 10% of Hubble constant. The results, published in 2001, also compared favorably with the Hubble flow calibrated with several secondary distance indicators that could also be used in more remote objects. Type Ia supernova is a category of cataclysmic stars that formed as the violent explosion of a white dwarf star. It produces consistent peak luminosity and is used as standard candles to measure the distance to their host galaxies. The brightnesses of Type Ia supernovae, being much brighter than Cepheids, are critical for measuring Hubble constant at even larger distances, and those measurements could be combined with the Cepheid values. At that point, one of Hubble's major objectives was achieved.

While the measurements of Hubble constant were converging to a consistent value, the simplest cosmological model in favor (the Einstein-de-Sitter model), used to convert the expansion rate into an age for the universe, resulted in a value of about 9 billion years. The situation was clearly impossible. The ever-refined globular cluster ages dropped slightly with better understanding of stellar astrophysics, but the big question in cosmology remained: 13 billion or 9 billion? The quandary was finally resolved for the most part with the discovery that the expansion rate is changing over time and the universe is actually accelerating, so the age derived from the simple model is not correct. The new model, which accommodates this circumstance, has resolved the discrepancy, resulting in an age of the universe of 13.7 billion years that is consistent with the independent globular cluster ages.

The story is not complete, however. A study reported in 2009, using Near Infrared Camera and Multi-Object Spectrometer data, produced a value of Hubble constant to within 5% uncertainty. This measurement represents a factor of two in improvement and is in general agreement with the key project report. The acceleration and age of the universe will continue to be investigated and refined. Thus, the determination of Hubble constant and the detailed nature of the expansion of the universe will be important research topics for future Hubble studies.

Interacting Galaxies

Galaxies occur in a variety of environments: small groups, such as those surrounding our own Milky Way; medium-sized and large clusters; and tight formations of interacting objects.



A small selection of the hundreds of interacting galaxies observed by Hubble.

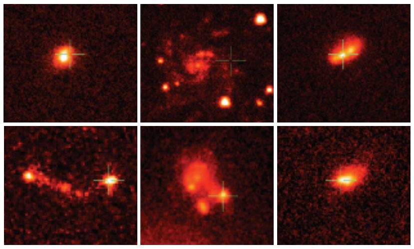
The study of interacting or colliding galaxies yields information about how galaxies may have formed and merged in the early universe and how star formation is triggered across the span of a spiral galaxy's disk. From the first days of Hubble observations to years later, magnificent images of pairs, groups, and small clusters of galaxies have been obtained for this research.

Gamma-ray Bursts

Knowledge of the existence of energetic bursts of emission in gamma rays from all across the sky was traced to the 1960s with the serendipitous detection of gamma-ray bursts by the US Vela satellites designed to detect gamma rays from nuclear weapon tests. The nature of the bursts was enigmatic and posed a problem for astrophysics once it was understood that the energy originated from somewhere in the sky. Data from the Burst and Transient Source Experiment instrument of the Compton Gamma Ray Observatory, launched in 1991, represented a watershed in understanding by demonstrating that gamma-ray bursts come from *everywhere* in the sky. The search was on until 1997 when another gamma-ray satellite, BeppoSAX, with an Italian/Dutch instrument, detected a gamma-ray burst called GRB 970228 associated with a fading x-ray emitter. The breakthrough in understanding came as scientists identified the optical counterpart in Hubble images and realized that the source resided in a distant galaxy. Hubble monitored the object and traced its rate of fading over time. The observations demonstrated that although the source was in a distant galaxy, it was not near its center, suggesting that the bursts were associated with a single object but not the galaxy's nucleus.

Hubble research identified a number of gamma-ray bursts over time, and all were attributed to objects in distant galaxies. For example, a staggeringly bright object in a host galaxy was identified with Wide Field Planetary Camera 2 after detections by the BeppoSAX and Compton satellites in 1997. In general, Hubble data are used to monitor the fading of the object months after the initial burst, when the emission is no longer observable by other facilities. An accumulation of such observations of over 40 objects with Space Telescope Imaging Spectrograph, Wide Field Planetary Camera 2, and, later, Advanced Camera for Surveys clarified that "long-duration" gamma-ray bursts reside in the brightest regions of small, irregular galaxies. The analysis suggests that the progenitors are massive stars, roughly 20 or more times the mass of the sun, in regions with a dearth of heavy chemical elements. Overall, gamma-ray bursts appear associated with some sort of stellar collapse sometimes involving magnetic fields and the creation of stellar black holes, often associated with supernovae explosions.

Hubble Wide Field Planetary Camera 2 recorded the brightest supernova gamma-ray burst that could be seen with the naked eye halfway across the universe. The explosion was so far away, it took its light 7.5 billion years to reach Earth. In fact, the explosion



Hubble images probing the environments of gamma-ray burst detections found that long-duration events are located in small, faint, misshapen, (irregular) galaxies, which are usually deficient in heavier chemical elements. Only one of the bursts was spotted in a spiral galaxy like our Milky Way. The burst sources are concentrated in the brightest regions of the host galaxies, suggesting they may come from some of the most massive stars, for example those that are 20 times the mass of the sun.

took place so long ago that Earth had not yet come into existence. This object may be a star more than 50 times the mass of the sun that had exploded much more violently than the "usual" supernovae. These objects, called *hypernovae*, fade more slowly than other gamma-ray bursts.

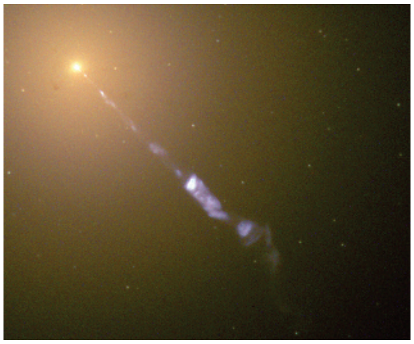
Black Hole Census

Astronomers had avidly searched for the existence of black holes in galaxies with a variety of instrumentation and telescopes, and it was spectroscopic observations of large galaxies that revealed that supermassive black holes might be quite common. After servicing mission 2, astronomers were able to employ a full suite of Hubble instruments to continue the ongoing inventory of black holes in galaxies. Researchers eventually inferred that the smaller black holes exist in smaller galaxies, so that a correlation between galaxy size and black hole mass was uncovered. Near Infrared Camera and Multi-Object Spectrometer and Wide Field Planetary Camera 2 data uncovered evidence for black holes in a growing list of objects. The detailed profiles of black holes were traced with spectroscopic data from Space Telescope Imaging Spectrograph. Astronomers observed material surrounding the cores of numerous galaxies. This material exhibited features particular to material spiraling into black holes. In addition, jets, bubbles, and dense star clusters were detected. A black hole also was discovered in our own galaxy's nearby companion, M31. The exotic nature of star clusters close to the black hole in the center of the Milky Way was characterized through infrared observations with Hubble. The picture that emerged is that black holes are pervasive in the center of galaxies rather than a rarity. Giant elliptical galaxies and spiral galaxies with enormous bulge components seem to be the hosts of supermassive black holes, whereas galaxies such as the Milky Way, with smaller bulges, have smaller black holes. Another link between galaxies and black holes is that it now appears that very active nuclei, called active galactic nuclei, and luminous quasars are linked to black hole and galaxy formation.

The black hole in the center of the giant elliptical galaxy M87 is the best studied with Hubble. Since Hubble was first launched, the instruments on board have been used to image the detail of the galaxy's core, the structure of its jet, and, more recently, the flare-up of the jet as observed with Advanced Cameras for Surveys and Space Telescope Imaging Spectrograph. The mysterious brightening and fading is likely due to activity around the black hole.

Astronomers also have pushed Hubble to observe smaller-sized black holes; for example, mapping the chaotic fluctuations in the ultraviolet light exhibited by Cygnus XR-1, one of the first stellar black holes known. The observations verified the existence of material sliding through the event horizon of the black hole. Apparently, medium-sized stellar black holes do exist as well, as determined from Wide Field Planetary Camera 2 images and Space Telescope Imaging Spectrograph spectroscopic observations of the globular cluster M15. Since these star clusters contain the oldest stars in the universe, they probably contained black holes when they originally formed. An intermediate-mass black hole was similarly discovered in the giant cluster "G1" in M31. With improvements in instrumentation coupled with excellent pointing stability, the multiyear Hubble black hole campaign has provided insights into the black holes in the violent cores of galaxies and possible linkages to stellar-mass black holes formed in the early universe.

Image of the entire galaxy M87 taken with Advanced Camera for Surveys.



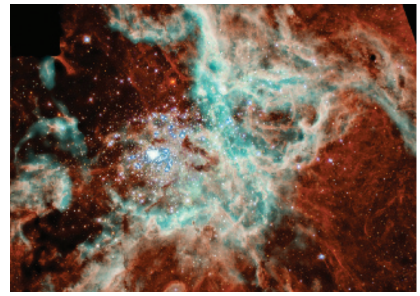
Detail of the jet and tight core containing an enormous black hole in the giant elliptical galaxy M87 reobserved with Hubble's Wide Field Planetary Camera 2.

Star Formation

Luminous nebulae comprised of ionized hydrogen with numerous and sometimes hundreds of young stars can be seen in our own galaxy, in nearby galaxies, and in distant galaxies. These star-forming regions are sites of clusters of stars containing some massive objects that are synthesizing many of the heavy chemical elements, later to be spewed out in stellar explosions. Studies of these objects with Hubble allowed the details of the nebulae to be mapped along with the interaction of the hot stars emitting intense ultraviolet radiation causing the nebular material to be ionized and glow. The first images of such regions included the Orion star-forming region and the Eagle Nebula.

One such huge complex is 30 Doradus—the largest in the local group of galaxies. It is located 170,000 light-years from Earth in the Large Magellanic Cloud, a companion galaxy to the Milky Way. It has been called an astronomical "Rosetta Stone" because detailed examination of the object gives a clue to the nature of star-forming regions that are seen, but unresolved, in distant galaxies across the universe.

The Orion Nebula is a star-forming region in our own galaxy and close enough to be seen in small telescopes as it is 1,500 light-years away. Because this region is so vast, the large mosaic image was created after the Advanced Camera for Surveys was installed. Detailed examination of parts of the image shows stars, gas, and dust as well as several regions revealing clusters of stars forming. The nebula itself is being disrupted by radiation from those stars, leaving loops, bubbles, and rings of material, all of which can be distinguished with the high-resolution Advanced Camera for Surveys composite.



The Wide Field Planetary Camera 2 image of 30 Doradus in the Large Magellanic Cloud contains one of the most spectacular clusters of massive stars, called R136, in our cosmic neighborhood of about 25 galaxies.

Image mosaic of the Orion Nebula exhibiting clumps of stars forming and the detailed sculpting of the nebula by radiation from the bright young stars formed there. (Hubble Advanced Camera for Surveys and European Southern Observatory at La Silla [Chile] 2.2-m [7.2-ft] telescope.)

With the installation of the infrared Wide Field Camera 3 during servicing mission 4, Hubble observers can peer into the dust of these tumultuous regions.

Stellar Death Throes

Planetary Nebulae

Some of the most photogenic nebulae are remnants of the last stages of stellar life, called planetary nebulae. These nebulae are formed from stars with mass similar to the sun while stars larger than eight times the solar mass end as supernovae. In small telescopes, these nebulae appear as roundish, smooth objects but, in fact, no two planetary nebulae are alike. With Hubble observations, it has become clear that planetary nebulae formation is very complex. Material is often ejected in rings and loops, and the nebulae chaotic structures suggest that these stars shed mass in several

The diversity of planetary nebulae is shown in this image. The nearly symmetric appearance of NGC 3132 in this Wide Field Planetary Camera 2 image shows the more "classic" morphology of a planetary nebula.

This nebula, called NGC 6543 or the Cat's Eye Nebula, was one of the first planetary nebulae to be discovered. The Advanced Camera for Surveys image shows how complex these objects can be. Planetary nebulae exhibit a huge range of diverse morphologies due to their formation process.

episodes. Some of the nebulae exhibit irregular streamers and nodules as well. It is likely that the interplay of stellar winds and radiation emitted by the star causes the structures, but the exact manner in which this occurs is still poorly understood.

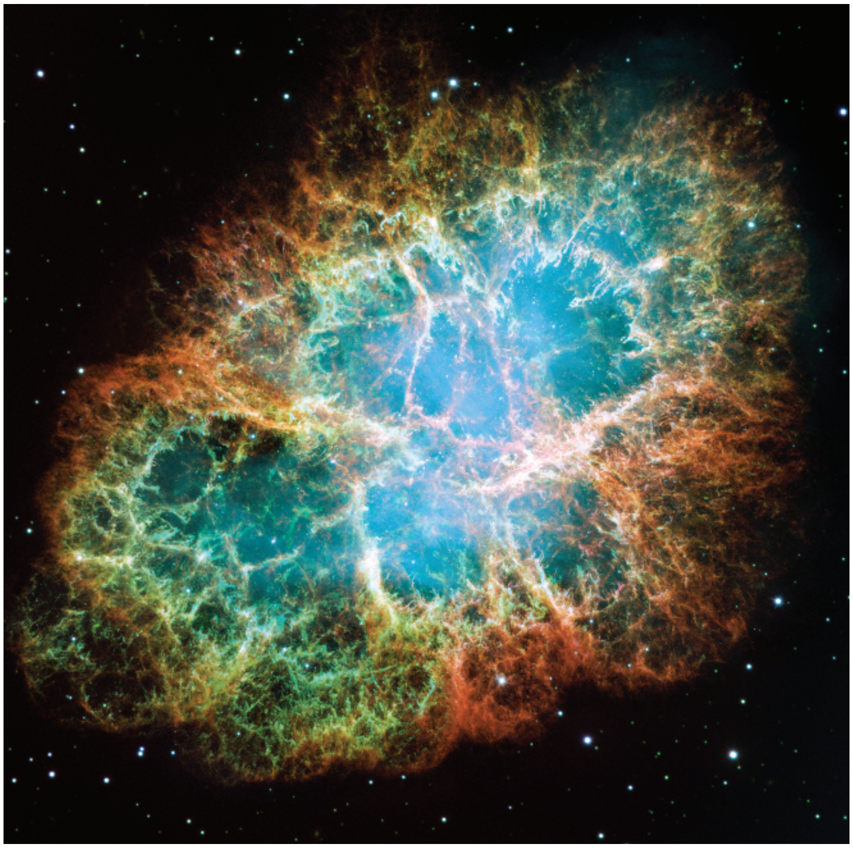
Supernovae and Supernova 1987A

Stars larger than about eight times the mass of the sun end their lives in a different, spectacular way as their nuclear fuel is exhausted. The violent explosion, a supernova, blows off a significant fraction of the star's mass into a nebula or remnant, emitting radiation from the x-ray to the radio. The resulting nebula is a complex twist of material and magnetic fields, giving these objects complicated shapes. The detailed, exceptional imagery from Hubble has allowed researchers to examine the morphologies of these objects.

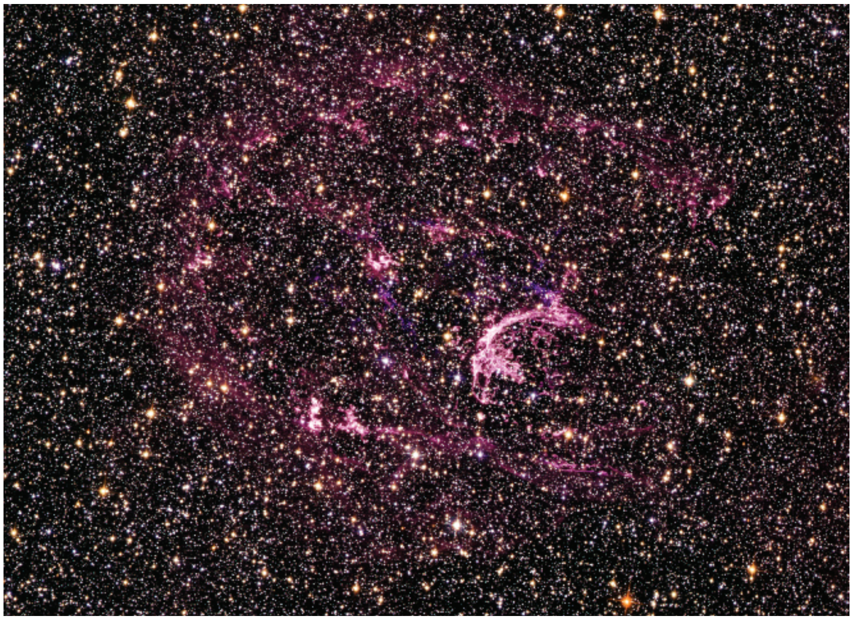
There are several classifications of supernova reflecting different features and formation mechanisms. The supernovae called type Ia are sometimes formed by binary stars. The importance of these types of supernova is that they appear to have a signature luminosity increase and a particular relationship between the various energies emitted. Because they have unique characteristics, they are considered "standard candles"; i.e., they have a known intrinsic brightness so that, when they are discovered in distant galaxies, the distance to them can be fairly accurately determined. These objects are lynchpins in the study of the expansion of the universe and the discovery of dark energy.

One well-known supernova in our own galaxy, the Crab Nebula, has been imaged by Hubble over several years. In addition to the intricate appearance of the nebula, the actual explosive event was witnessed by Japanese and Chinese astronomers in 1054 and most likely was also seen by Native Americans.

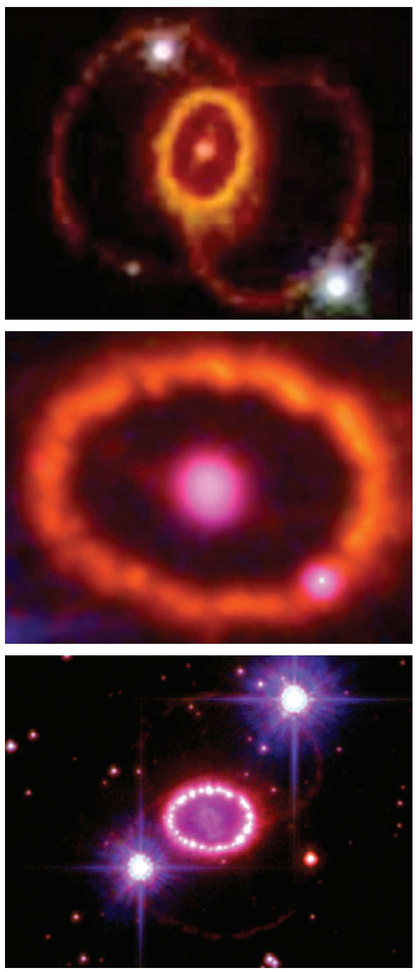
Many supernovae remnants in the galaxy are so large they cannot be imaged easily with a few exposures of Hubble. The supernova remnant called N132D is one of several such objects imaged by Hubble. It is located in



A giant mosaic of Wide Field Planetary Camera 2 observations of the Crab Nebula, compiled from observations accumulated in 1999 and 2000.



This Advanced Camera for Surveys and Wide Field Camera 3 image is of supernova remnant N132D in the Large Magellanic Cloud.



Light from the explosion illuminated the remnant material around supernova 1987A. The Wide Field Planetary Camera 2 images revealed an hourglass structure evidenced in the two overlapping rings. The central ring is apparently in a plane parallel to the other rings, which are in front of and behind the central ring as seen from this vantage point. The upper image was obtained in 1994. The next image, also obtained in 1994, shows the brightening of the inner ring caused by the explosion shockwave impacting the ring. Twenty years after the explosion, Hubble was able to resolve multiple sites that were illuminated due to the shockwave continuing to expand outward into the remnant material from prior events. The lower image, from Advanced Camera for Surveys, shows the fully illuminated ring and the outer ring structure from 2006.

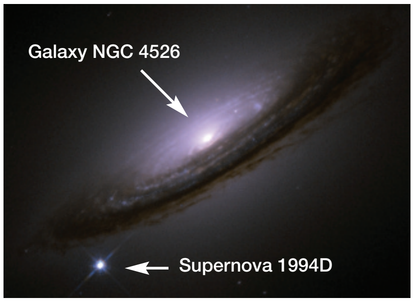
the Large Magellanic Cloud, close enough for detailed examination, but sufficiently far away to allow the whole structure of the nebula to be examined. The observation of N132D is actually a composite of the newly restored Advanced Camera for Surveys, repaired during servicing mission 4, and the new Wide Field Camera 3. A spectrum of this object was also obtained with the new Cosmic Origins Spectrograph instrument to analyze the chemical composition of the nebula.

The most famous and scientifically important supernova is supernova 1987A, an object that exploded in the Large Magellanic Cloud in February 1987. The light from the explosion expanded outward and illuminated material far from the progenitor star, suggesting prior outflows and explosions may have occurred. Astronomers have used nearly every Hubble camera to monitor changes in supernova 1987A. Merged with observations from other observatories, the Hubble images have contributed to the understanding of this particular object. This information also has helped with understanding of type Ia supernovae in general.

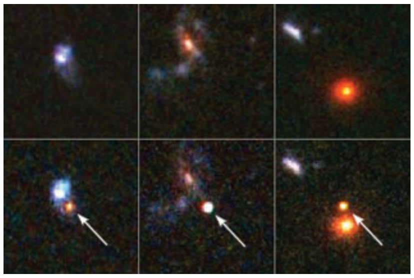
Dark Energy

At its inception, Hubble was designed to determine the age of the universe through measurements of cosmological expansion—the value of Hubble constant. Every improvement in instrumentation, computing systems, and telescope capability has led to greater knowledge and sometimes extraordinary results about the cosmos. As details of the universe's expansion unfolded, astronomers derived an unexpected nuance of the expansion. It appears from Hubble observations that the universe is not expanding at a constant rate or slowing down under the tug of gravity as astronomers expected. Instead its expansion is speeding up and has been for the past 4 to 5 billion years.

A key to this discovery is the understanding that, like Cepheid variables, supernovae can be used as distant light posts or standard candles, but supernovae are about a million times brighter. One type of supernova explosion, a *Type Ia Supernova* (abbreviated SN Ia), is thought to explode as a result of binary stars exchanging matter. The explosive output, 1-2 x 10^{44} joules or about 3.5 x 10^{28} megatons of TNT, has a specific profile: a fast rise in a few hours or days and a decline over about a month or so. These objects also achieve a more or less typical intrinsic brightness—the characteristic that makes SN Ia a valuable standard for measuring the distances to its very remote host galaxies in which the supernova is imbedded.



Supernova 1994D in galaxy NGC 4526 can be seen as the bright star in the lower left corner of this Hubble Wide Field Planetary Camera 2 image.



Images of three of the most-distant supernovae known, discovered using the Advanced Camera for Surveys.

Steven Hawley, PhD
Astronaut on STS-41D (1984), STS-61C (1986), STS-31 (1990), STS-82 (1997), and STS-93 (1999).

"I have been very fortunate to be among a very small group of individuals to have seen the Hubble Space Telescope in space—twice. A memory that I will cherish forever is seeing the Hubble Space Telescope as we approached on STS-82, 7 years after I released it from Discovery in April 1990. To see Hubble Space Telescope once in a career is special, but to see it twice is truly a privilege. I remember when we were able to see the back side of Hubble Space Telescope for the first time on the 1997 mission. Hubble Space Telescope keeps one side preferentially pointed at the sun and that side is opposite the side to which you approach in the shuttle to grapple the telescope. When we saw the far side, we were able to see that the thermal insulation resembling aluminum foil looked brittle and had peeled away from the telescope in some locations. Prior to the last extravehicular activity for that mission our crew was asked to fabricate some temporary patches from material that we had on board and to install them over some of the worst damaged sites. Before we did that we all signed the foil patches, so for a while my signature was on the Hubble Space Telescope."

Hubble was employed along with several powerful ground-based telescopes to seek out and measure SN Ia across the universe. Hubble Wide Field Planetary Camera 2 was first used to map SN Ia and then deep Advanced Camera for Surveys observations probed the most distant supernova. The amassed observations helped refine Hubble constant. Since the measurements extended to some of the farthest reaches of the universe, it was possible to use all the SN Ia observations pieced together to measure another important cosmological parameter: the cosmological constant. The cosmological constant was proposed by Einstein in his General Relativity as a kind of "repulsive gravity," a means of keeping the universe static so that it would not collapse under its own gravity. When he learned from Edwin Hubble that the universe is not static but is in fact expanding, Einstein removed the cosmological constant from his equations (and referred to it as "my greatest blunder"). The observations by the Hubble Space Telescope and its partner ground-based telescopes that the expansion of the universe is in fact accelerating under the influence of some completely baffling force, a kind of repulsive gravity, strongly suggests that the cosmological constant may not have been a "blunder" after all.

This result is problematic as we currently do not have a succinct theory to explain why this situation exists. For example, we know the Big Bang that originated the universe causes objects to recede from each other when measured over cosmological distances. We also know that gravity is the retarding force that slows the expansion due to mutual attraction between all matter in the universe. Therefore, either the universe would keep expanding because there is not enough matter (gravity) to slow it or its expansion would slow (decelerate) because there is enough gravitational force to retard that expansion. Acceleration of the expansion does not fit into this picture. The unexplained cause of the acceleration, called dark energy, is the focus of additional observations and theoretical work. The existence of the acceleration has been confirmed by detailed analysis of the Wilkinson Microwave Anisotropy Probe observations designed to measure the cosmic microwave background, the remnant radiation from the Big Bang. Other observations of x-ray emission, further observations of supernovae, and other results have contributed to the confirmation of this puzzle.

Needless to say, the discovery of evidence for dark energy was not predicted for Hubble or for any other observatory constructed to date. This significant problem in physics and astrophysics is expected to be a driving part of the design for new telescopes to be commissioned in the next decade.

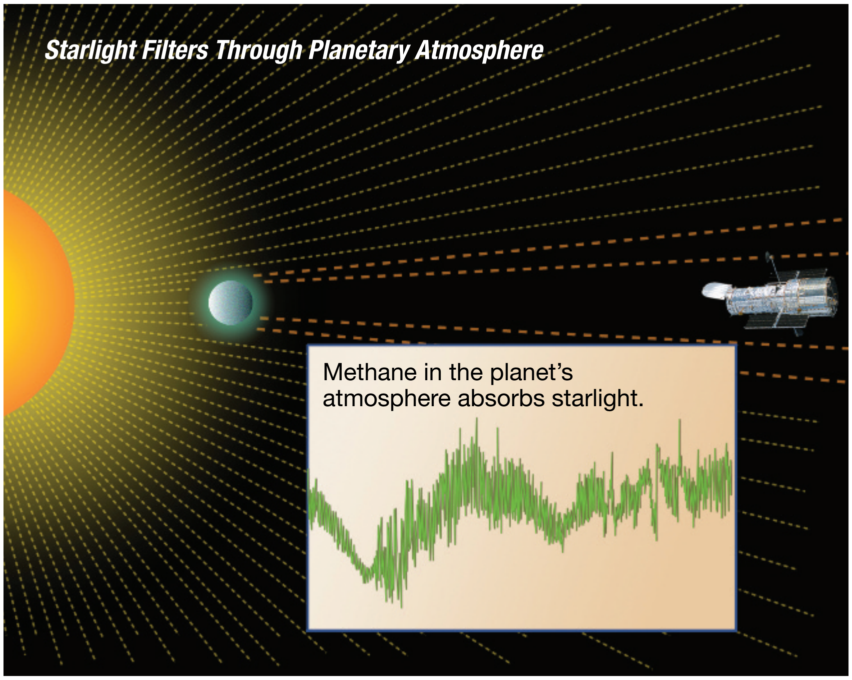
This is an image of a gravitational lens obtained after servicing mission 4 with the newly repaired Advanced Camera for Surveys camera. Abell 370 is one of the very first galaxy clusters where astronomers observed the phenomenon of gravitational lensing.

Dark Matter

An interesting phenomena produced by gravitational fields is *gravitational lensing*. A warping of space by a large mass such as a cluster of galaxies can distort light from more distant objects. The distortions appear as shreds of images, stretched into arcs and streaks. Gravitational lenses are of interest for two main reasons: first, the very distant objects can be analyzed since the lens also enhances the brightness of the far galaxy or luminous quasar; and second, the total mass of the lensing cluster can be determined. The total mass is a composite of luminous mass (the galaxies detected by Hubble) plus dark, unseen matter. Reconstruction of the mass distribution gives clues to the nature of dark matter that cannot be seen through telescopes. Such observations also were combined and used to create a three-dimensional map of dark matter in the universe, although the true nature of the material is still unknown.

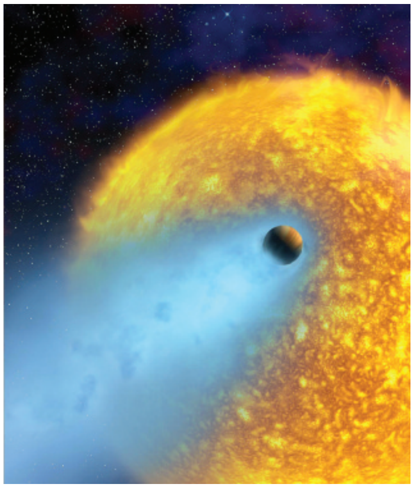
Extrasolar Planets

A planet outside the solar system is commonly categorized as an extrasolar planet. Scientists have made confirmed detections of 473 such planets. The vast majority were detected through velocity calculations observations and other indirect methods rather than actual imaging. The search for planets forming around other stars has been a consistent theme in research conducted with Hubble. Besides probing star-formation regions, Hubble is used to detect planetary disks around stars where planets are likely to be forming. While it was not expected that Hubble would contribute significantly to the detection and characterization of extrasolar planets, the opposite has been true.



An illustration of the spectrum obtained from an extrasolar planet and the configuration of the parent star, the planet, and Hubble to obtain the observation.

In 2001, Hubble observed the first transit of an extrasolar planet across the disk of its parent star. The yellow dwarf star HD 209458 has a Jupiter-sized planet in a tight, 3½-day orbit around it. The extremely close orbit causes the planet to lose its atmosphere; i.e., the atmosphere is blowing off its surface into space. It is the planet plus the atmospheric material that caused a slight dip in the brightness of the star that could be observed with precise observations.

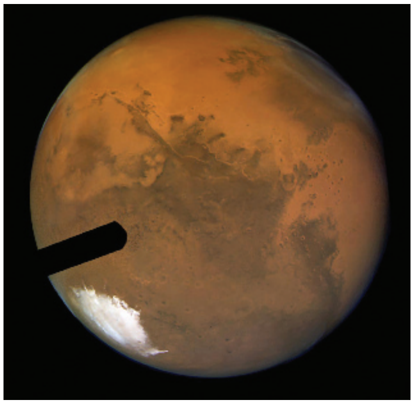


Scientists reported the first-ever optical detection of an extrasolar planet, which passed in front of a huge star in the constellation Pegasus. This transit dimmed the light of the star by a measurable 1.7%. This shows the capability of Hubble to detect extrasolar planets.

In 2007, Hubble actually detected the atmosphere of an extrasolar planet, a new achievement in planetary research. The light from the star passed through the atmosphere of the planet and was detected by Hubble's Near Infrared Camera and Multi-Object Spectrometer. The atmosphere contains methane, carbon dioxide, carbon monoxide, and water molecules. This exciting observation was an important achievement because it demonstrated that prebiotic materials are present in the atmosphere of at least one extrasolar planet, and that as such measurements are possible with Hubble they bode a bright future for such research with the James Webb Telescope.

Solar System

Hubble has not been idle in contributing to the understanding of our solar system objects. The first spectacular solar system observation was that of the 1994 crash of Comet Shoemaker-Levy 9 into Jupiter. Subsequently, Mars is and has been actively researched with Hubble. Wide Field Planetary Camera 2, Near Infrared Camera and Multi-Object Spectrometer, Space Telescope Imaging Spectrograph, and Advanced Camera for Surveys have all monitored weather conditions, observed seasonal changes, mapped the polar caps, watched dust storms, and conducted remote "site surveys" of landing spots for Martian probes. In the Advanced Camera for Surveys image of the sharpest Earth-based image ever taken of Mars, small craters and other surface markings only about a few tens of kilometers (a dozen



An Advanced Camera for Surveys image of Mars exhibiting the sharpest view ever taken from Earth. In view are numerous craters, several large volcanoes of the great Tharsis plateau along the upper left limb, and a large multi-ring impact basin, called Argyre, near image center. There is a reddish tinge over the southern ice cap suggesting dust contamination in the clouds or the ground ice.

miles) across can be seen. Hubble continues to support the NASA Mars mission and probe activities.

Other phenomena observed include the changing atmosphere of Jupiter, spectacular views of Jupiter's moons, the rings of Saturn in various phases, an aurora on Uranus, clouds on Neptune, and the first map of the surface features of Pluto. Hubble observations contributed to the characterization of asteroids and support of NASA probes landing on such objects, discovery of outer solar system Kuiper belt objects, and measurements of Quaoar and the dwarf planet Eris. The latter observations, in concert with data from the W.M. Keck Observatory in Hawaii, helped lead to the reclassification of Pluto as a "dwarf planet."

Most Popular Results

In addition to extensive research results obtained through the use of Hubble observations, public enthusiasm for NASA's endeavors—and Hubble in particular—is a consequence of the open and active press release system for Hubble.

Public understanding of astronomy and somewhat of science in general comes from the free availability of Hubble results. Particular images become popular by nature of their image quality, such as nebulae and galaxies. Other images are fascinating due to the astrophysical processes they depict, such as extrasolar planets, the distant universe, and Mars. Many images are also used in education to improve science literacy. All Hubble press release material can be found at: *http://hubblesite.org/newscenter/archive/releases/YEAR/PR.*

Hubble Scorecard

The initial primary driver for Hubble was cosmological studies; specifically, the determination of the age of the universe. Other important research areas involved the nature of galaxies and black holes, and the details of the intervening material permeating the universe. Below are a few examples of the anticipated and unanticipated science results. The qualities of Hubble, such as diffraction limited, high-sensitivity imagery, excellent spectroscopic capability, and high-contrast imaging from the ultraviolet through the visible to the infrared has provided for the exemplary science achieved.

Anticipated science:

- Measurement of the expansion rate of the universe since the Big Bang
- Confirmation of the existence of massive black holes in galaxies and a census of less-massive black holes in smaller galaxies and black holes in binary star systems
- Observation of emission revealing the physical nature of energetic active galactic nuclei
- Discovery of the host galaxies associated with enigmatic quasi-stellar objects (quasars)
- Detection of the intergalactic medium and the interstellar medium through absorption of light from distant quasars

Unanticipated science:

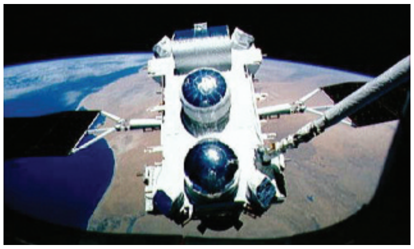
- Characterization of conditions for galaxy formation in the early universe through mergers and black hole formation
- Detection of the acceleration of the universe corresponding to the discovery of dark energy, the cosmic mechanism that counteracts the slowdown of the universe caused by gravity
- Unveiling the nature of gamma-ray bursts through identification of the host galaxies
- Observations of planetary disk formation
- Detection of extrasolar planets and several atmospheres of planets orbiting other stars

Other Science and Technology

The development of Hubble and its relationship to the shuttle, as well as other NASA programs, yielded advances in science and technology beyond discoveries about the universe. The advancement of optical and infrared detectors for use in space and the evolution of various sensors, circuitry, and navigation systems are all part of the contribution toward technologies needed to support the science and instrumentation. Other benefits of the program include the manufacture of robust electronic chips, hard drives, computation systems, and software. The science and technology required for human and robotic space exploration transformed due to the partnership between the Hubble science endeavor and the Space Shuttle Program.

Compton Gamma Ray Observatory

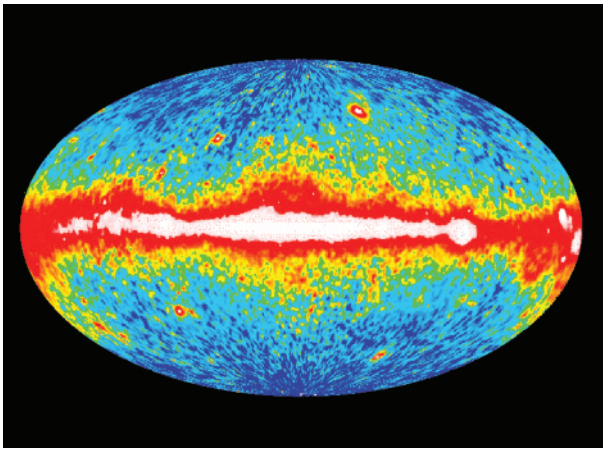
Hubble was the first Great Observatory, while Compton Gamma Ray Observatory was the second. Its launch on Space Shuttle Atlantis (Space Transportation System [STS]-37) in 1991 represented a benchmark in shuttle lift capability since it was the heaviest astrophysical payload flown to date. As planned, Compton spent almost a decade enabling insight into the nature and origin of enigmatic gamma-ray sources and was safely deorbited and reentered the Earth's atmosphere on June 4, 2000. The observatory was named in honor of Nobel Prize winner Dr. Arthur Compton for his physics research on scattering of high-energy photons by electrons, a critical process in the detection of gamma rays.



Compton Gamma Ray Observatory being prepared for deployment from Atlantis, STS-37 (1991).

Instrumentation

Compton was designed to detect high-energy gamma-ray emissions caused by diverse astrophysical phenomena including solar flares, pulsars, nova and supernova explosions, black holes accreting material, quasars, and the bombardment of the interstellar medium by cosmic rays. Four scientific instruments—Burst and Transient Source Experiment, Oriented Scintillation Spectrometer Experiment, Imaging Compton Telescope, and Energetic Gamma Ray Experiment Telescope—were intended to cover the high end of the electromagnetic spectrum.



Can you imagine "seeing" gamma rays? This computer-processed image allows you to "see" the entire sky at photon energies above 100 million electron volts. These gamma-ray photons are 10,000 times more energetic than visible-light photons and are blocked from reaching Earth's surface by the atmosphere. A diffuse gamma-ray glow from the plane of our Milky Way is seen across the middle belt in this image.

While previous gamma-ray missions sampled astrophysical sources (after the original chance detection of gamma rays by the Vela military satellite in the 1960s), Compton pushed to a factor of 10 sensitivity improvement in each instrument. Based on the spectacular results, specifications emerged for new gamma-ray satellites.

Compton Science Results

All-sky surveys are an important tool for uniformly mapping the sky and understanding the overall relationship of various components of the nearby neighborhood as well as the universe. The Energetic Gamma Ray Experiment Telescope instrument provided a high-energy map that demonstrated the interaction between the interstellar gas that pervades the disk of our galaxy with cosmic rays. The telescope also sampled variable extragalactic sources such as quasars that emit in high-energy "blazers."

All-sky maps also were obtained with the Imaging Compton Telescope and Oriented Scintillation Spectrometer Experiment. The Imaging Compton Telescope surveyed a narrow energy band of gamma rays. It also detected neutrons from a solar flare early on in the program. The Oriented Scintillation Spectrometer Experiment survey mapped the center of our galaxy and was also sensitive to solar flares caused by accelerating particles colliding with the sun's surface.

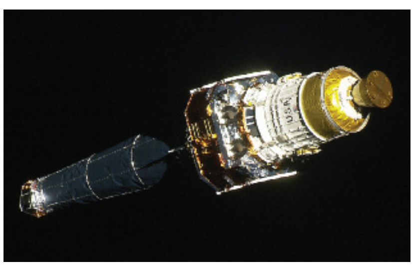
The workhorse of the Compton observatory was the Burst and Transient Source Experiment, designed to detect gamma-ray bursts. The first result was to confirm that the bursts came from all over the sky, suggesting a cosmic origin rather than a local solar neighborhood cause or some phenomena restricted to our galaxy. The brief flashes were eventually traced to chaotic events, some associated with the collapse of stars in distant galaxies. The instrument also detected gamma-ray burst repeaters and a few sources that were identified by monitoring x-ray sources and watching them wink out as the Earth occulted the object. These discoveries began to narrow in on the types of phenomena that could produce gamma rays.

Compton ended its impressive science career in 1999 with a gyro failure. A safe re-entry into Earth's atmosphere was successfully executed in 2000.

The Chandra X-ray Observatory

NASA named its x-ray observatory to honor the scientific achievements of American Astrophysicist Dr. Subrahmanyan Chandrasekhar who was awarded the Nobel Prize in Physics (1983) for his theoretical studies of the physical processes of importance to the structure and evolution of the stars.

X-rays are emitted by a plethora of objects including galaxies, exploding stars, black holes, and the sun. The Chandra X-ray Observatory was designed to probe x-ray emitters across the universe. When Chandra was deployed from Space Shuttle Columbia—Space Transportation System (STS)-93 (1999)—it was the longest satellite and provided a new heaviest-science-payload benchmark. Chandra is the third Great Observatory launched by NASA.



Chandra X-ray Observatory.

Scientific Research with Chandra

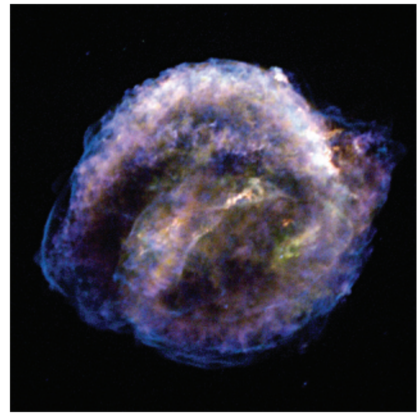
Chandra detected many types of sources, but the nature of black holes definitely caught the attention of both the scientific community and the public. Even in our own locale, the black hole at the inner 10 light-years of our galaxy was mapped. This source emits x-rays due to the extremely hot temperature (millions of degrees) of the material that has been gravitationally captured by the black hole and is spiraling into it. Chandra detected a "cool" black hole at the center of the Andromeda Galaxy, and more black holes were found that were confirmed as "supermassive" black holes in other galaxies.

Chandra data on individual stars have shown that binary star systems in collapse can produce x-rays, and normal stars in formation can produce x-rays through their stellar winds. Chandra showed that nearly all normal stars on the main sequence emit x-rays.

Chandra also provided a gallery of observations of supernova remnants. Research allowed scientists to understand how some supernovae are produced by binary stars, and how remnant neutron stars and pulsars interact with their surroundings. The dynamic of the shock wave, interactions with the interstellar medium, and the origin of cosmic rays are all in evidence in the x-ray emissions. The detailed compositions and distribution of the ejecta are traced in the x-rays.

Chandra also provided insight into the "hard x-ray" background—energies in the 2-10 keV range was a mystery for several decades. Some of these sources appear to be quasars as expected, and others are associated with nuclei of active galaxies that are fainter and possibly obscured by surrounding dusty material.

Observations of the "deep fields"—the Hubble Deep Fields and also the fields selected to survey deep x-ray emission—bolster the idea that some sources are quasars and active galaxies. The supermassive black holes in these objects cause intense x-rays to be emitted. Other distinct sources are galaxies with modest x-ray luminosity.



The Chandra image of one of the youngest supernova remnants in the galaxy, Kepler's supernova. This remnant may have been produced by the collapse of a single star relatively early in its lifetime.

Gamma-ray bursts were mysterious sources. Once the gamma ray is detected, rapid scheduling of telescopes allows the observation of the afterglow, including in the x-ray. Chandra data can assist in the determination of the elements present near the object.

The combined observations of optical, infrared, and x-ray emission from clusters of galaxies led to the identification of dark matter. It is suspected that most of the universe is filled with dark matter and the luminous material represents a few percent of the universe's contents. Observations of several clusters of galaxies showed that the collision of these massive clusters left a clump of dark matter behind. This implies that dark matter is not exactly the same as the luminous material seen in optical images of the galaxies in the clusters. The material left behind also produces impressive gravitational lensing of more distant objects. What dark matter is exactly remains a mystery.

Eileen Collins
Colonel, US Air Force (retired).
NASA's first woman Space Shuttle pilot and commander.
Pilot on STS-63 (1995) and STS-84 (1997).
Commander on STS-93 (1999) and STS-114 (2005).

The Chandra X-ray Observatory: One of the shuttle's many success stories

"On July 23, 1999, I had the incredible privilege of commanding the Space Shuttle Columbia, which took the Chandra X-ray Observatory into space.

"Some fun facts about Chandra: the observatory can focus so well it could read a newspaper at half a mile. If the surface of the Earth was as smooth as Chandra's mirrors, the highest mountain would be no greater than 1.8 m (6 ft) tall.

"STS-93 was a dream mission for me. Not only did I have an opportunity to command a shuttle mission, I could marry it with a longtime hobby: astronomy. When I was a child in Upstate New York, I would look to the stars at night and feel inspired and excited. I wanted to travel to each one of those points of light, know what was there, what were they made of. Were there people there?

"I moved to Oklahoma for US Air Force pilot training. The wide open, dark, clear skies encouraged me to buy my first telescope. I bought books and magazines on astronomy and spent most of my spare time reading! Many shuttle astronauts came to Vance Air Force Base for training. This combination of exposure to the night skies and the emerging Space Shuttle Program inspired me to plan my career around my eventual application to the astronaut program!

"After over a year of training for STS-93 and several unexpected launch delays, my crew headed to the launch pad on July 20, 1999, which coincided with the 30th anniversary of Apollo 11. Our launch was manually halted at T minus 8 seconds by a sharp engineer who saw the 'hydrogen spike' in the aft compartment. A sensor had failed, and we were subsequently cleared to launch again in 2 days. After a single weather scrub, we rescheduled for the 23rd and lit up the sky shortly after midnight. Well, this was no ordinary launch! Five seconds after liftoff, we saw a 'Fuel Cell pH' message, received a call from Houston about an electrical short, which took out two main engine controllers! Unbeknownst to us, there was a second problem: at start-up, a pin had popped loose from a main engine injector plate. It hit several cooling tubes, causing us to leak hydrogen. Due to the shuttle redundancy and robustness of the main engines, they did not fail. The shuttle fleet was grounded to conduct thorough wiring inspections, resulting in many lessons learned for aging spacecraft.

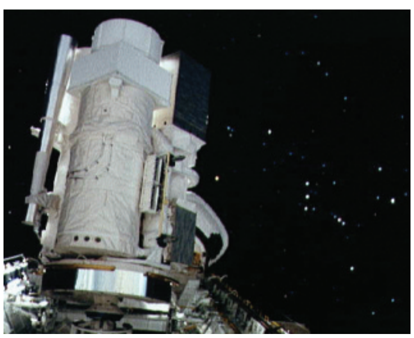
"Despite the launch issues, I believe it was the right decision to launch Chandra on the shuttle vs. an expendable launch vehicle. The mission reaped the benefits of a human presence. True, a shuttle launch is more costly, but it is similar to buying insurance for missions with irreplaceable payloads.

"Today, the Chandra X-ray Observatory is increasing our understanding of the origin, evolution, and destiny of the universe. It is an incredible product of human ingenuity. The data will be around for generations of worldwide scientists to digest as we discover our place in the universe. I see Chandra as an expression of our curiosity as humans. As we search to discover what makes up this wondrous universe we live in, creations like Chandra will be far and away worth the investment we put into them. Chandra is one of the successful, productive, and mighty success stories of the Space Shuttle Program!"

Other Space Science Missions

Ultraviolet Programs

NASA devoted two shuttle flights to instrument packages designed to study the ultraviolet universe. A pallet of telescopes called the "Astro Observatory" were mounted together to fly several times. Astro-1 comprised three ultraviolet telescopes and an x-ray telescope while Astro-2 concentrated on the ultraviolet. Astro-1 flew on Columbia—Space Transportation System (STS)-35 (1990)—and Astro-2 flew on Endeavour—STS-67 (1995). The missions were designed to probe objects in the solar system, our galaxy, and beyond. Data on supernovae such as the Crab Nebula, planetary nebula, globular clusters, and young stellar disks were obtained.



Space Shuttle Columbia (STS-35) carries Astro-1 for observations of the ultraviolet universe in December 1990.

Exploring Stellar Surfaces: Hot and Cold Stars

The Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer Shuttle Pallet Satellite missions were designed to be free-flying missions supported by the shuttle. Space Shuttle Discovery (STS-51) deployed this satellite in 1993, the first of a series of missions. Ultraviolet spectra of hot stars, the coronae of cool stars, and the interstellar medium were observed. The second mission observed nearly 150 astronomical targets including the moon, nearby and more distant stars in the Milky Way, other galaxies, a few active galaxies, and the energetic quasar 3C273.

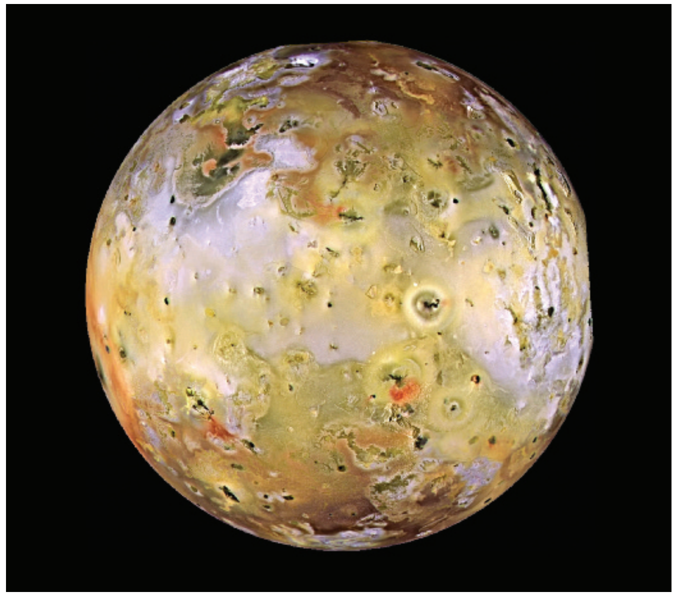


Image of Jupiter's moon Io obtained with the Galileo spacecraft. Io has the most volcanic activity in the solar system, giving it this mottled appearance. Features down to 2.5 km (1.6 miles) in size are seen along with mountains, volcanic craters, and impact craters from asteroids and comets.

Chasing Jupiter and Its Moons

NASA's Galileo Mission was designed to study Jupiter and its system of moons. The spacecraft was launched by Space Shuttle Atlantis (STS-34) in 1989. Galileo was fitted with a solid-fuel upper stage that accelerated the spacecraft out of Earth orbit toward Venus. Galileo arrived at Jupiter and entered orbit in December 1995. The spacecraft orbited through the Jovian system, measuring the moons as well as the planet Jupiter. Galileo sent a probe into Jupiter's atmosphere, finding the planet's composition to differ from that of the sun—important for understanding how the solar system formed. It provided the first close-up views of the large moons—Io, Europa, Ganymede, and Callisto—showing the dynamic Io volcanic activity and evidence that Europa may have a frozen surface with liquid underneath. Discoveries of many new moons around Jupiter, flybys of asteroids, and an interaction with a comet are part of Galileo's accomplishments. The spacecraft also was fortuitously in position to image the full sequence of more than 20 fragments of Comet Shoemaker-Levy impacting Jupiter in 1994.

The Galileo mission ended on September 21, 2003, when the spacecraft plummeted into Jupiter's atmosphere. From launch to impact, Galileo traversed trillions of kilometers (miles) on a single tank of gas, not counting the fuel for the shuttle. The total amount of data returned during its 14-year lifetime was 30 gigabytes, including 14,000 memorable pictures.

Studying the Anatomy of the Sun

On February 14, 1980, NASA launched the Solar Maximum Satellite (SolarMax) aimed at studying the maximum part of the sun's cycle. During this intense period, the sun's surface activity is characterized by massive ejections of high-energy particles extending into the solar system. SolarMax's life was almost cut short by a malfunction, but it fortunately was extended due to servicing by Space Shuttle Challenger (STS-41C) in 1984. Astronauts performed maintenance and repairs by replacing the attitude control system and one of the main electronics boxes, demonstrating that satellites could be repaired successfully and given extended life when serviced by the shuttle. SolarMax's career ended with re-entry on December 2, 1989.

The SolarMax instruments were mainly designed to study the x-ray and gamma-ray emissions from the sun. Two of the instruments also were capable of observing celestial sources outside the solar system. Observations showed that due to the bright faculae in the vicinity of dark sunspots are so intense that they increase the overall brightness of the sun. Therefore, the sun not only emits many charged particles but is also more intense during sunspot maximum.

The Magellan Mission: Mapping Venus

The Magellan spacecraft was launched on May 4, 1989, by Space Shuttle Atlantis from Kennedy Space Center, Florida, arrived at Venus on August 10, 1990, and was inserted into a near-polar elliptical orbit. Radio contact with Magellan was lost on October 12, 1994. At the completion of radar mapping, 98% of the surface of Venus was imaged at resolutions better than 100 m (328 ft), and many areas were imaged multiple times. The Magellan mission scientific objectives were to study land forms and tectonics, impact processes, erosion, deposition, and chemical processes and to model the interior of Venus. Magellan showed us an Earth-sized planet with no evidence of Earth-like plate tectonics.

Our Amazing Star: The Ulysses Mission

To fully understand our amazing star, it was necessary to study the sun at near maximum conditions. During the solar maximum, Ulysses reached the maximum Southern latitude of our sun on November 27, 2000, and traveled through the High Northern latitude September through December 2001.

After more than 12 years in flight, Ulysses had returned a wealth of data that led to a much broader understanding of the global structure of the sun's environment—the heliosphere.

Summary

Many hundreds of years ago, our ancestors came out of their caves, gazed at the stars in the sky, and wondered, "How did we get here?" and "Are we alone?" They likely asked themselves, "Is there more out there?" and "How did this world begin?" They tried to comprehend their place in this complex puzzle between the Earth and the skies. We live in an age that has seen an explosion of science and technology and the beginnings of space exploration. We are still asking the same questions.

The Space Shuttle played a significant role in leading us toward some of the answers. Space science missions discussed here are opening a new window on our universe and providing a glimpse of galaxies far beyond.

Clearly, the partnership between the Space Shuttle Program and the Hubble Space Telescope, as well as other missions, contributed to the science productivity and outstanding reputation of NASA as a science-enabling agency. The obstacles that faced NASA throughout the journey were actually stepping-stones that led to a higher level of understanding not only of the universe, but of our own capabilities as a space agency and as individuals.

> *"…and measure every wand'ring planet's course,*
>
> *Still climbing after knowledge infinite…"*
>
> – Christopher Marlowe